THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 28, NUMBER 12 DECEMBER, 1957

Automatic Spectrometer Using Interference Filters

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(Received April 12, 1957; and in final form, July 18, 1957)

A new automatic spectrometer is described, based on the use of interference filters. It yields spectra of light sources, reflecting surfaces and filters well within one second. It may be adjusted for obtaining integral spectral values and color coordinates of the above objects within one second.

I. INTRODUCTION

By using modern interference filters,[1–7] narrow spectral bands may be obtained. As an example, the experimental transmitting curve of such a filter is shown in Fig. 1. If a succession of suitable interference filters is passed between a radiation source and a radiation receiver (e.g. photomultiplier), a corresponding succession of electrical impulses may be obtained at the output of the receiver. These impulses may be amplified and applied to one pair of deflection plates of an electrostatic cathode ray tube. The other pair of deflection plates may be connected to a voltage source, the tension of which corresponds to the filter, which is just being passed before the radiation receiver. Thus, a series of pulses will appear on the cathode ray screen, the height of which corresponds to the spectral intensity passed by each filter, whereas the horizontal scale corresponds to the wavelength.

The realization of this basically simple idea involves several considerations, some of which will be briefly discussed here. Some further data on the application of interference filters to spectroscopy were published in previous papers.[8–13]

The shape of the transmission curve of a filter, the wavelength λ_0 of optimal transmission and the optimal transmission coefficient depend on the angle of incidence and on the polarization of the incident radiation. Hence the angle of incidence should be kept within narrow bounds. The transmission coefficient τ as dependent on the deviation $\Delta\lambda$ from the wavelength λ_0 of optimal transmission τ_0 may be expressed in many cases by the approximate equation

$$\tau(\Delta\lambda)=\frac{\tau_0}{1+[\Delta\lambda/(\Delta\lambda)_0]^2}, \qquad (1)$$

where $(\Delta\lambda)_0$ is the value of $\Delta\lambda$ corresponding to $\tau=\tau_0/2$. This equation is illustrated by the dashed curve of Fig. 1. If the radiation source has a known intensity wavelength relation $W_1(\Delta\lambda)$, and the photoreceiver has

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a known sensitivity $p(\Delta\lambda)$, the measured value M_1 of radiation intensity will be

$$M_1=\int_{-(\Delta\lambda)_1}^{(\Delta\lambda)_2} W_1(\Delta\lambda)\tau(\Delta\lambda)p(\Delta\lambda)d(\Delta\lambda). \tag{2}$$

The values $(\Delta\lambda)_1$ and $(\Delta\lambda)_2$ correspond to the boundaries λ_1 and λ_2 of transmission of the filter; $(\Delta\lambda)_1=\lambda_0-\lambda_1$; $(\Delta\lambda)_2=\lambda_2-\lambda_0$. If the transmission curve of the filter is sufficiently narrow, and if $W_1(\Delta\lambda)$ corresponds to a continuous spectrum without spectral lines in the filter transmission region, we may write approximately

$$W_1(\Delta\lambda)p(\Delta\lambda)=a_1+b_1\Delta\lambda. \tag{3}$$

Inserting (3) and (1) into Eq. (2), we obtain

$$M_1=a_1\tau_0 H\tan^{-1}[2(\delta\lambda)/H], \tag{4}$$

where

$$\begin{aligned}H&=2(\Delta\lambda)_0\ \text{(see Fig. 1)},\\ (\Delta\lambda)_1&=(\Delta\lambda)_2=\delta\lambda,\\ a_1&=p_0W_{10},\\ p_0&=p\ \text{at}\ \lambda=\lambda_0,\\ W_{10}&=W_1\ \text{at}\ \lambda=\lambda_0.\end{aligned}$$

If a second radiation source of unknown intensity $W_2(\Delta\lambda)$ is placed before the filter, a value M_2 is obtained

$$M_2=a_2\tau_0 H\tan^{-1}[2(\delta\lambda)/H], \tag{5}$$

where

$$a_2=p_0W_{20}.$$

Hence

$$W_{20}=(M_2/M_1)W_{10}. \tag{6}$$

In reality, the filter transmission curves are not exactly symmetrical with reference to λ_0. This may be taken into account by

$$\left.\begin{aligned}\tau(\Delta\lambda)&=\frac{\tau_0}{1+[\Delta\lambda/(\Delta\lambda)_{10}]^2}\quad\text{for}\quad -(\Delta\lambda)_1\leqq\Delta\lambda\leqq 0;\\ \tau(\Delta\lambda)&=\frac{\tau_0}{1+[\Delta\lambda/(\Delta\lambda)_{20}]^2}\quad\text{for}\quad 0\leqq\Delta\lambda\leqq(\Delta\lambda)_2.\end{aligned}\right\} \tag{7}$$

Thus, almost exact correspondence between calculated and measured transmission curves may be obtained. Using (7), the resulting deviation from Eq. (6) may be calculated

$$M_2/M_1=W_{20}K/W_{10}. \tag{8}$$

The value of

$$(K-1)/K=k \tag{9}$$

is a measure for the relative error caused by the asymmetry. This error has been calculated for 17 particular filters, starting from some particular intensity and sensitivity curves. The results show that the relative error k is in all cases below 7% and in most cases below 3%.

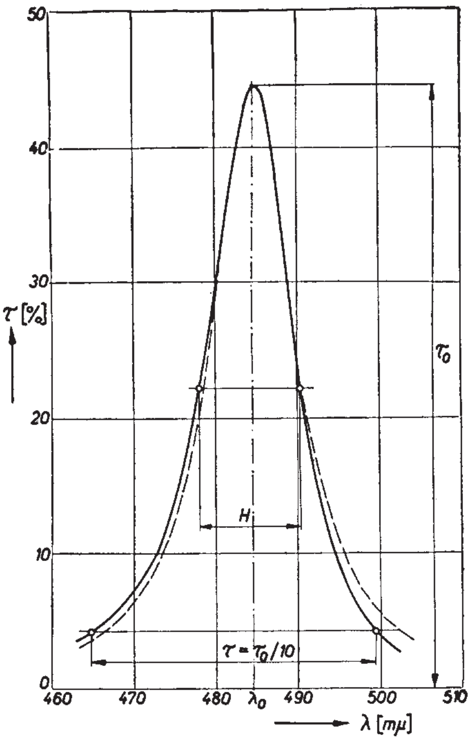

FIG. 1. Experimental transmission (full) curve. Transmission coefficient τ (vertical) as dependent on wavelength λ (horizontal). Indication of width H, where $\tau=\frac{1}{2}\tau_0$ and of the width, where $\tau=\frac{1}{10}\tau_0$. Dashed curve is approximation of experimental full curve by Eq. (1).

In the above discussion a linear relation, as in Eq. (3) was assumed for W_1 as well as for W_2 within the bounds of transmission of the filter. If these relations are no longer valid, a better approximation may often be obtained from

$$W_1(\Delta\lambda)p(\Delta\lambda)=a_1+b_1\Delta\lambda+c_1(\Delta\lambda)^2. \tag{10}$$

In some practical cases, the radiation source emits spectral lines superimposed on a continuous spectrum. In this case a compensation method may be applied, using a source of known intensity curve (without spectral lines) $W_1(\Delta\lambda)$ and a second source of intensity curve $\bar{W}_1(\Delta\lambda)$, which has a line spectrum, identical to that of the source to be measured (W_2). The intensity corresponding to the continuous spectrum of $\bar{W}_1$ is measured by a suitable separate spectrograph ($\bar{W}_{1k0}$). If now $\bar{W}_1$ is measured with the filter spectrometer, a value $\bar{M}_1$ is obtained. By suitable compensation at the electrical output of the filter spectrometer, $\bar{M}_1$ is adjusted, until

$$\frac{\bar{M}_1}{M_1}=\frac{\bar{W}_{1k0}}{W_{10}}. \tag{11}$$

In this case, the output corresponding to the line spectrum of $\bar{W}_1$, being: $\bar{M}_{1L}=\bar{W}_{1L}p_{1L}\tau_{1L}$, is exactly compensated. As, by supposition, $\bar{W}_{1L}p_{1L}\tau_{1L}=W_{2L}p_{2L}\tau_{2L}$, we obtain

$$M_2/M_1=W_{2k0}/W_{10}, \tag{12}$$

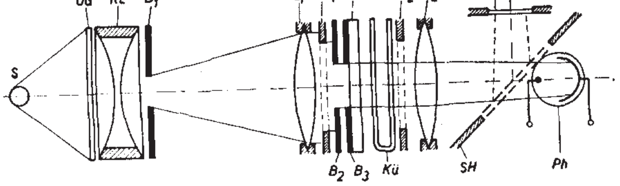

FIG. 2. Optical system between light source S and photoreceiver Ph. A description is given in the text.

thus measuring the continuous part of W_2 with our filter spectrometer. The electrical compensation, mentioned here, will be dealt with in detail in Sec. III.

II. OPTICAL AND MECHANICAL CONSTRUCTION

The filter spectrometer should be applicable to sources emitting self-radiation as well as reflected radiation, and also to transmission spectra of sheets and of liquids. The radiation, incident on the filters, should be as nearly perpendicular to the filter surface as possible, in order to avoid errors resulting from alterations of the filter curves at oblique incidence. The optical system is shown schematically in Fig. 2. The radiation source S illuminates the diffusor OG (opal glass). The condenser lens KL causes a homogeneous illumination of the central hole in the iris diaphragm B_1. The lens L_1 is a corrected projection objective of 4 parts, 1:2,8, having a focal distance of 150 mm. The diaphragm B_1 is situated at the focus of L_1. The divergence of the radiation passed by L_1 depends on the hole in B_1. If the radius of this hole is 2.5 mm, the maximum deviation from perpendicular incidence on the filter surface is 1°. At a hole radius of 20 mm, it is 7.5°. No larger radii are used. At an incidence of 7.5°, the optimal wavelength λ_0 of a filter at 550 mμ is deviated by 1.4 mμ from its nominal value at perpendicular incidence. As this represents the maximum deviation at a hole radius of 20 mm, the incidence condition may be assumed to be satisfactorily met. Behind L_1 is the filter support FH_1. Here, any filter, the transmission curve of which is to be determined, may be inserted. Also a suitable gray filter may be inserted, if the intensity of radiation should be excessive. B_2 is a variable slit diaphragm, serving to exclude spurious radiation. A second adjustable slit B_3 is situated before the interference filter F. By B_3 the sensitivity of the spectrometer may be adjusted for each interference filter. A suitable glass container may be inserted at Ku in order to measure the transmission spectrum of liquids. A further filter support FH_2 serves equally as does FH_1. A second projection objective L_2, similar to L_1, concentrates the radiation on the photomultiplier Ph (RCA 6217). A mirror support SH is inserted between L_2 and Ph, inclined at 45°. Using a suitable mirror the radiation may be projected on the frosted disk M. The multiplier Ph may be moved to the position M, thus permitting the measurement of spectral curves of reflecting surfaces, inserted at SH.

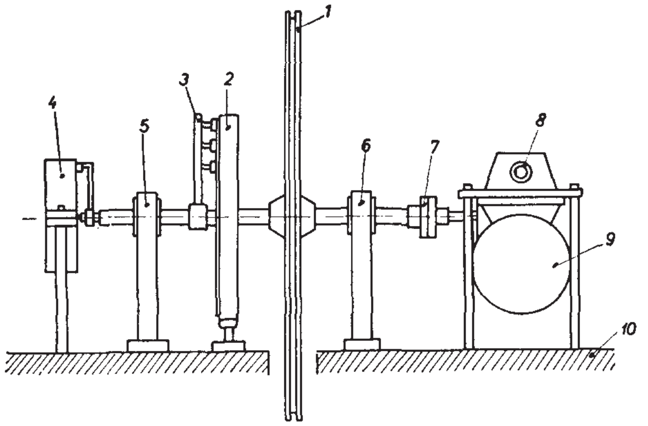

FIG. 3. Schematic diagram of mechanical construction of filter spectrograph. A description is given in the text. (1) steel wheel with interference filters; (2) commutator disk; (3) contact arm; (4) potentiometer; (5) and (6) supports of axis; (7) coupling; (8) gear box; (9) motor; (10) steel plate.

In total, 25 interference filters are being used, manufactured at Geraetebauanstalt Balzers, Liechtenstein. The optimal wavelengths of these filters are: 385, 400, 413, 428, 441, 456, 472, 486, 498, 511, 527, 539, 553, 567, 581, 595, 608, 622, 638, 655, 667, 680, 695, 707, 722 mμ. Their H values (see Fig. 1) are between 4 and 17 mμ and their transmission values τ_0 are between 15 and 47%.

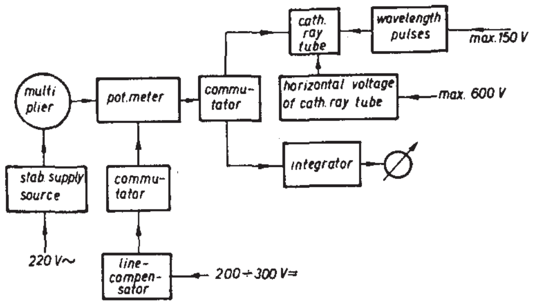

FIG. 4. Schematic diagram of electrical circuit of automatic filter spectrograph. A description is given in the text.

The mechanical part of the spectrometer is shown schematically in Fig. 3. The filters are arranged at the circumference of a steel wheel (1 in Fig. 3) of 500 mm diameter. This wheel has 360 holes of 2 mm diameter at a circle of 488 mm diameter. These holes correspond to a wavelength scale, 1 degree corresponding to approximately 1 mμ. As the wavelengths go from 380 to 730 mμ, a 10° part of the circumference is not used. The filter supports are fastened to the wheel by pins, inserted in the above 2-mm holes. Hence the optimal wavelengths of the filters may be adjusted with an accuracy of 1 mμ. The minimal distance between two subsequent filters is determined by their dimensious and amounts to 12 mμ in wavelength. Hence 29 filters could be used in total. In order to account for tolerances of optimal wavelengths, 25 filters are actually being

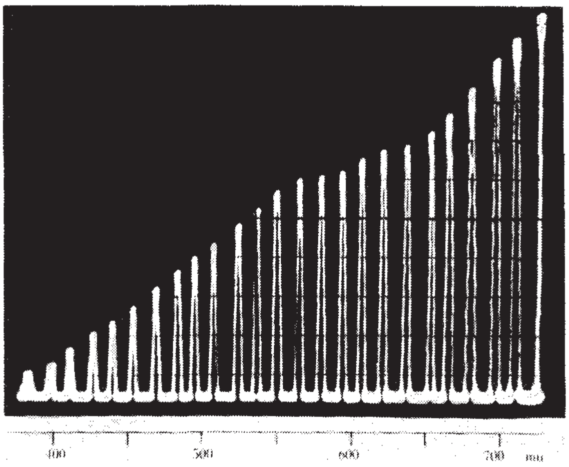

FIG. 5. Spectrum of a "daylight" incandescent lamp as obtained by the automatic spectrometer.

used, the mean filter distance being hence approximately 14 mμ. By rotating the wheel, the filters pass subsequently through the position F of Fig. 2, thus passing subsequent radiation pulses to the photomultiplier Ph.

A contact arm (3 of Fig. 3) is fastened on the wheel axis and operates contacts on the commutator disk (2). Furthermore, a second contact arm, also fastened on the wheel axis, operates a potentiometer (4).

III. ELECTRICAL CIRCUIT

A block diagram of this circuit is shown in Fig. 4. The filter wheel axis is driven by a 270-watt single phase commutator motor of 5000 rpm, using a gear box of 30:1. Hence the wheel axis rotates at a maximum speed of 166 rpm. Practically, this speed will often be chosen to be about 60 to 120 rpm, by regulating the supply voltage of the motor.

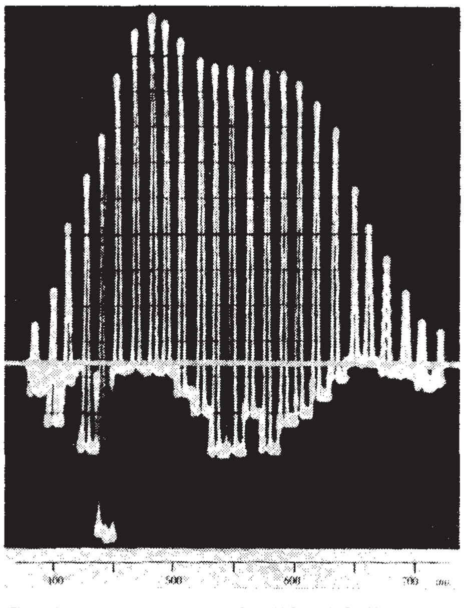

FIG. 6. Continuous spectrum of a "daylight" fluorescent lamp, obtained by electrical compensation of the emission line intensities The horizontal white line is the zero line for the spectral intensities. Below this line the marks made by the line compensation voltages may be seen.

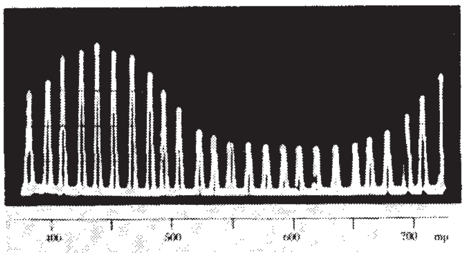

FIG. 7. Re-emission spectrum of a blue paper, obtained by the automatic spectrometer.

The output of the photomultiplier is connected to a suitable potentiometer arrangement (see Fig. 4) and thence via the commutator disk (2 of Fig. 3), acts on one pair of deflection plates of the cathode ray tube. The commutator disk carries three pairs of contact tracks. The outer track generates the electrical impulses, marking the wavelength scale on the oscillogram. The other two tracks have 25 divisions each, corresponding to the 25 filters of 14 degrees each and a subsidiary part of 10 degrees. Contacts are made by means of small steel cylinders, rolling along the bronze tracks.

The sensitivity of the spectrometer may be altered by means of a potentiometer circuit, varied continuously by means of a potentiometer, which is connected to the output of the photomultiplier.

The compensation of spectral lines, as mentioned in Sec. I, may be carried out by means of a suitable circuit.

IV. APPLICATION

Of the manifold possible applications only a few characteristic ones will be mentioned for sake of brevity. The absolute sensitivity of the spectrometer was adjusted with the aid of a standard incandescent lamp, the spectrum of which was previously determined by means of a prism spectrograph. A spectral curve obtained for a "daylight" incandescent lamp is shown in Fig. 5. The measured values have been compared with exact values obtained for this lamp from the Swiss Federal Bureau of Standards at Bern (Dr. F. Maeder). The maximum error of the automatic spectrograph was 6.5%. Most individual errors of the 25 pulses were below 1.5%.

The errors are of the order of magnitude mentioned in Sec. I. They are relatively larger at smaller measured

TABLE I.

Color coordinates	measured values x	y	Standard values x	y
"Daylight" Incandescent lamp	0.422	0.408	0.424	0.411
Lamp with green bulb	0.336	0.511	0.338	0.514
"Daylight" fluorescent lamp	0.325	0.355	0.322	0.352

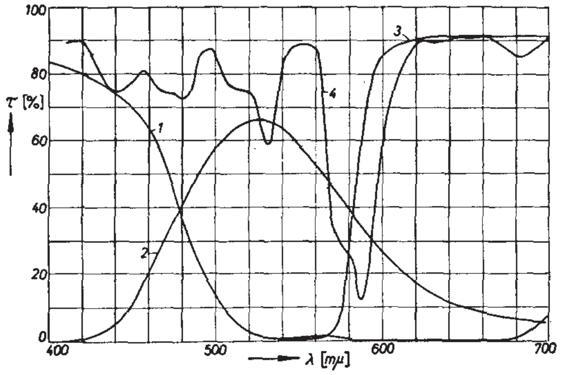

FIG. 8. Spectral transmission curves of a blue filter (1), a green filter (2), a red filter (3), and a didymium filter (4), obtained by means of a nonrecording normal Zeiss prism spectrograph.

intensities and vice versa. At points where the variation $dW/d\lambda$ is larger the relative errors are more important, as should be expected.

As an example, wherein the compensation of spectral line intensities, mentioned in Secs. I and III, is actually applied, Fig. 6 shows the spectral curve of a "daylight" fluorescent lamp. The continuous spectral curve appears above the zero line, whereas the compensation pulses for the lines appear downwards from the zero line.

In determining the relative transmission spectrum of filters, the spectrometer is first adjusted with a given light source, so as to yield equal pulses at all wavelength without the said filter. This is then inserted at FH_1 of Fig. 2.

Similarly as with transmission spectra, re-emission spectra may be obtained. As an example, Fig. 7 is shown for a blue paper.

According to international standards the color coordinates in the color triangle of a light source may be

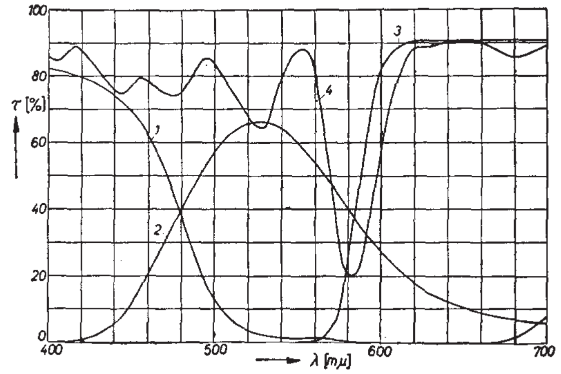

FIG. 9. Spectral transmission curves of the same filters, as mentioned in Fig. 8, but obtained by means of a General Electric recording spectrograph (by A. C. Hardy).

determined from three defined integral values obtained from the spectral curve. This was carried out as mentioned in Sec. III and also by standard calculation from spectral curves, obtained by means of a prism spectrograph (Table I).

It seems interesting to compare results, obtained with the present spectrometer with those of well-known other automatic spectrographs. We have selected for the latter the General Electric recording spectrograph (by A. C. Hardy).[15] Spectrographic curves, obtained with (a) a normal Zeiss nonrecording prism spectrograph, (b) the said General Electric spectrograph, and (c) the present automatic spectrometer on the same glass filters are shown, respectively, in Figs. 8, 9, and 10. Here it is seen, that the results of (b) and (c) are practically equivalent, whereas (a) is obviously more accurate.[16]

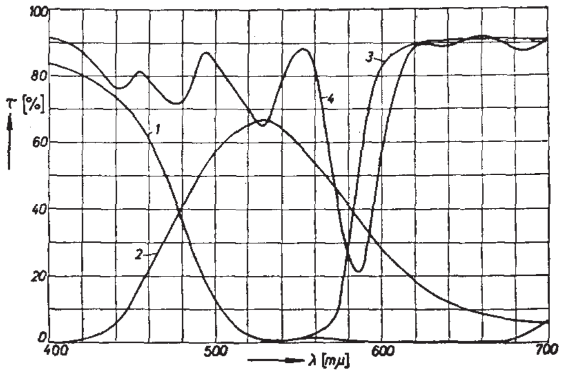

FIG. 10. Spectral transmission curves of the same filters, as mentioned in Fig. 8, but obtained by means of the automatic spectrometer, described here.

An automatic spectrometer according to the above principles is now being produced industrially by the Swiss firms of Pretema AG Zürich and Standardwerke AG Zürich. A prototype was shown at the Basel spring industrial exhibition 1957.

ACKNOWLEDGMENTS

The work described above has been made possible by a grant from the Swiss Federal foundation for the advancement of industry by scientific research. The authors take pleasure in expressing their sincere thanks for this grant. Mr. F. Goetz has devotedly constructed a first prototype, for which we wish to express our thanks.

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[16] The authors are greatly indebted to Professor J. Eggert of Zürich and to Dr. W. Schulze for the opportunity of obtaining these filter glasses.